Adjoint-based acoustic wave sensitivity of double-stream jet flow

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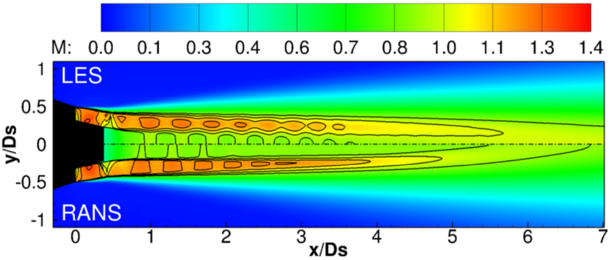
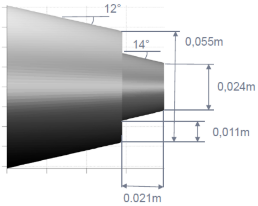
Roadmap

Context & Introduction

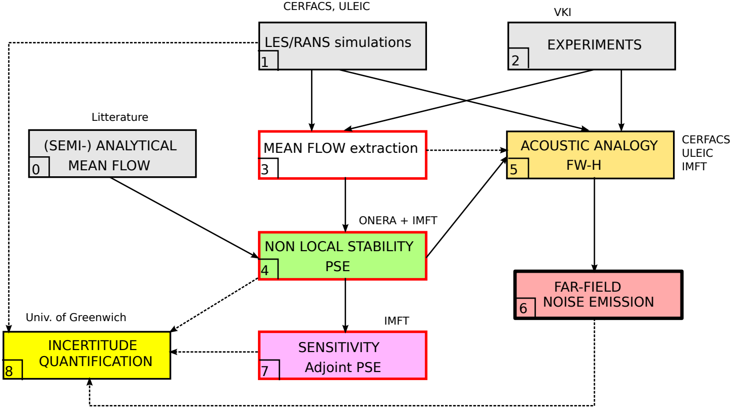
- Marie Curie "AeroTraNet 2" network, 9 participants (Airbus, CERFACS, VKI, ...), 2012 - 2016
- Investigate theoretically, numerically and experimentally the noise emission in a double-stream jet (shock cells noise)
- Ultimate goal : physical understanding of sound sources, noise propagation and control strategy for that flow
- 3D Configuration:





(Cerfacs)

Current work : summary of the procedures



Today the focus is on the blocks from 3 to 6 :

☞ base flow / stability / sensitivity

Current work

1. **Linear non local Stability Analysis (PSE)** :
   - relationship between noise sources and instability of turbulent mean flow and large scale structures (Barone & Lele, Colonius, ...)
   - single frequency analysis versus wide band-width spectrum of the turbulence
   - fast and efficient methodology which can lead to some optimal control approaches Airiau et al (2001, 2003), Wei & Freund (2006), Spagnoli & Airiau (2008), Sesterhenn & al (2012)
2. Sensitivity :
   - determine gradient of any suitable quantity w.r.t. any flow forcing
   - first analysis of possible actuation means and actuator locations
   - preambule and first step to find a noise control strategy

Known litterature

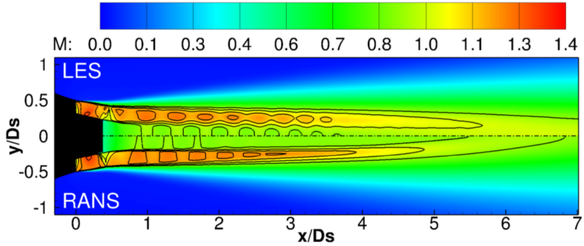
Many references in various part of the present work and beyond !

- Receptivity, sensitivity (incompressible, compressible) , resolvent: Hill (1995), Airiau(1999), Cervino & Bewley (2003), Spagnoli & Airiau (2008), Hu et al (2012), Luchini & Bottaro (2013), Jeun et al(2016), Sartor, Sipp,McKeon, Sharma, ...
- Optimal control (adjoint) : Collis et al (2001), Walter et al (2001), Wei & Freund (2006), Schulze et al (2011), Foysi et al (2014), Sipp, ...
- Stability / single stream jet / wave packets : Colonius and co workers, Goldstein et al (2005), Jordan, Cavalieri, Brazier et Léon, Lesshafft...
- Shock cell noise + stability : Barone & Lele (2007),...
- CAA, LES, Single stream jet aeroacoustics, sound radiation, ... : Bodony & Lele (2008), Agarwal(2014), Anurag, Sinayoko, Sinha, Rodriguez, Nichols, Bogey, Brès, Puigt, Davilliers, ...

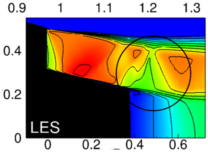
Dual-stream jet, LES Cerfacs

	Primary jet	Secondary jet	comment
M	0.89	1.20	supersonic
Pressure ratio	CNPR=1.675	FNPR = 2.45	
Diameters	$D_p = 23.4mm$	$D_s = 55mm$	
Reynolds ($\times 10^{-6}$)	0.57	1.66	Based on D_p
P_t (hPa)	1.6972	2.4825	$P_{amb} = 101325Pa$
T_t	T_{amb}	T_{amb}	$T_{amb} = 283K$, cold

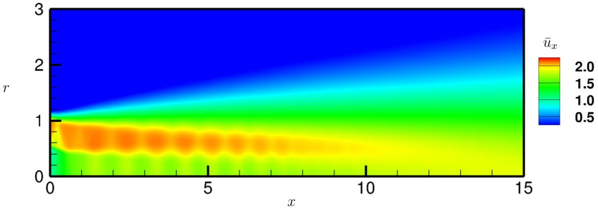
CNPR and *FNPR* stand for Core and Fan Nozzle to Pressure Ratio



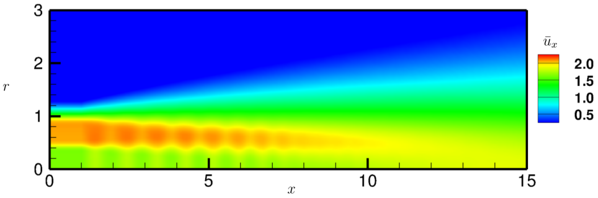
Strong shock cell at nozzle lip



Dual-stream jet, mean velocity $\bar{U}_x$



(a)



(b)

Strong non parallel flow close to the first shock cell, high instability : smoothing procedure to initialize the PSE .

Non local stability : PSE

- Herbert & Bertolotti (1991), Airiau(1993), ... Léon & Brazier (2015), Colonius et al, ..., code from ONERA
- spatial stability theory, taking into account of streamwise variations
- inviscid flow formulation justified by the inflectional nature of the instability and the wave propagation physics
- linear study: good approximation in the potential core w.r.t. the complexity of non linear PSE
- disturbance $(m = 0$ or $m = 1)$:

$$\boldsymbol{q}'(x, r, \theta, t) = \boldsymbol{q}(x, r) \;\; \mathrm{e}^{i\Theta(x,\theta,t)}, \qquad \Theta = \int_{x_0}^{x} \alpha(\xi) d\xi + m\theta - \omega t$$

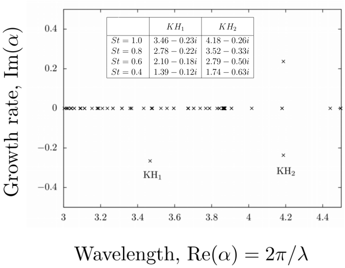
- "almost" parabolic PDE + Normalization condition

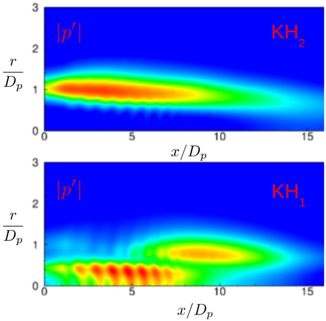
$$L_{PSE}\,\boldsymbol{q} = \boldsymbol{0}, \qquad \text{with} \quad L_{PSE} = i\alpha A_1 + imA_2 - i\omega A_3 + B + A_1 \frac{\partial}{\partial x} + A_0 \frac{\partial}{\partial r}$$

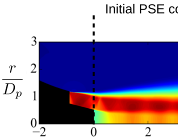
$$\mathcal{N}(\boldsymbol{q}) = \int_0^{\infty} (N\boldsymbol{q})^h \frac{\partial N\boldsymbol{q}}{\partial x} \; m_r \, dr = 0 \quad + \text{B.C.} + \text{I.C.}$$

- downwind marching procedure, addition of the procedure for small streamwise step $(\Delta x < \dfrac{\lambda}{2\pi})$, to solve accurately close to the nozzle exit (Andersson, 1998)

Dual-stream jet, 2 KH modes, $St = 1$

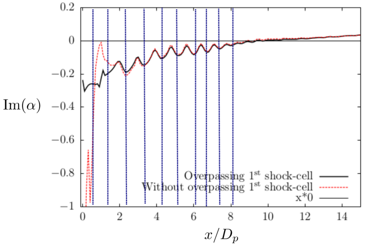


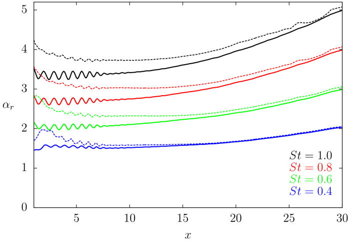


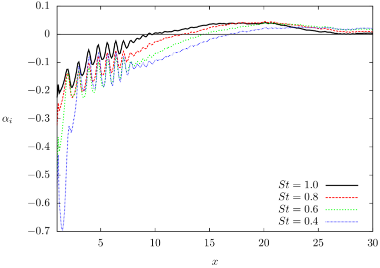


- without the nozzle lip shock
- 2 Kelvin-Helmholtz modes $\Longrightarrow$ 2 initializations with PSE
- Most unstable mode is dominant finally, exchange of stability w.r.t. x for KH_1 ?

Growth rate and wave number







a) effect of mean flow smoothing

b) Initialization with KH_1 and KH_2

c) Growth rate (smooth mean flow, KH_2)

1. Shock cells influence the natural flow instability
2. S_t decreases, λ increases, more unstable
3. 2 zones: $x < 8$ and $x > 8$, limit : last shock cell

Sensitivity: theory overview (PoF 2001, 2003)

1. variation of the global quantity associated to the disturbances :

$$E = \frac{1}{2}\int_{x_0}^{x_f} \underbrace{\int_0^\infty \boldsymbol{q}'^h M \boldsymbol{q}' \ m_r \ dr}_{E_x(x)} \ dx + \ell_f E_f + \ell_0 E_0$$

2. Lagrangian approach (Walther et al, PoF 2001, Airiau et al, PoF 2003, AIAA papers 2015 & 2016) :

$$\mathcal{L} = E - \langle \hat{\boldsymbol{q}}^*, \chi L_{PSE}\boldsymbol{q} - \boldsymbol{f}\rangle_\Omega - \int_{x_0}^{x_f} n^{*h}\langle \boldsymbol{q}, \frac{\partial \boldsymbol{q}}{\partial x}\rangle_r \, dx - \langle \hat{\boldsymbol{p}}_0^*, \boldsymbol{q}(x_0, r) - \boldsymbol{q}_0\rangle_r + c.c.$$

3. Sensitivities :

$$\frac{\partial E}{\partial f_k}\delta f_k = \left\langle \hat{q}_k^*, \delta f_k \right\rangle_\Omega + c.c.$$

$$\frac{\partial E}{\partial \omega}\delta\omega = i\chi_f \left\langle \boldsymbol{q}^*, A_2 \boldsymbol{q}\right\rangle_\Omega + c.c.$$

$$\frac{\partial E}{\partial \hat{q}_{0k}}\delta \hat{q}_{0k} = \left\langle \hat{p}_{0k}^*, \delta\hat{q}_{0k}\right\rangle_r + c.c.$$

Details in AIAA papers:

$$\chi L_{PSE}\boldsymbol{q} = \boldsymbol{f}, \qquad \chi(x) = \mathrm{e}^{i\int_{x_0}^{x}\alpha(\xi)d\xi}$$

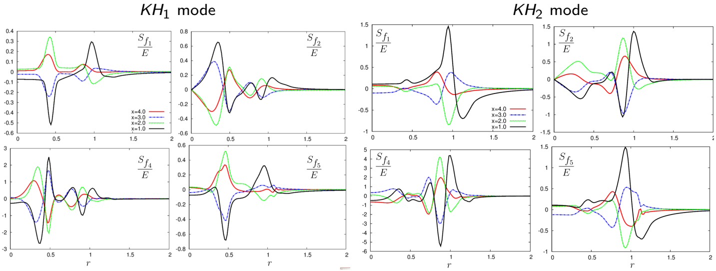
$$\hat{\boldsymbol{q}}^* = \chi^* \boldsymbol{q}^* \quad \hat{\boldsymbol{p}}_0^* = \chi^* \boldsymbol{p}_0^*, \quad \chi\chi^{*h} = \chi(x_f) = \chi_f$$

$$\chi_f^h L_{PSE}^* \boldsymbol{q}* = \frac{\partial\left(n^*\boldsymbol{q}\right)}{\partial x} - n^{*h}\frac{\partial \boldsymbol{q}}{\partial x} + \ell\chi\chi^h \boldsymbol{q}$$

$$\ell E_x + \chi_f \frac{\partial \left\langle \boldsymbol{q}^*, A_0\boldsymbol{q}\right\rangle_r}{\partial x} = 0 \quad + \mathrm{B.C.} + \mathrm{T.C.}$$

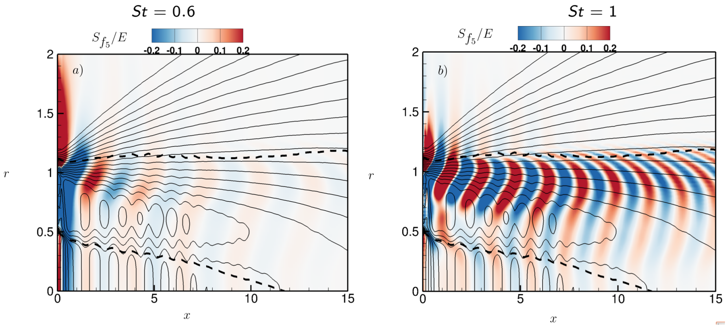
upwind marching procedure + Newton-Raphson for n^*
(different from Tissot et al (AIAA-2015-2218))

Sensitivity Analysis : KH initialization



- maximun of sensitivity in the shear layers where the mode is the most unstable
- highest sensitivity close to the nozzle exit
- $S_{f_1} \rightarrow$ source of mass and $S_{f_5} \rightarrow$ source of energy are similar
- $S_{f_2} \rightarrow$ source of $m_r = \rho u_r >> S_{f_4} \rightarrow$ source of $m_x = \rho u_x$
- KH_2 sensitivities are higher than KH_1 ones
- Complex variations in r between the two shear layers, with some zeros.
- Globaly the sensitivities strongly depend on the instability and therefore of the mean flow physics

Sensitivity Analysis : Frequency and inflection points (KH_2)



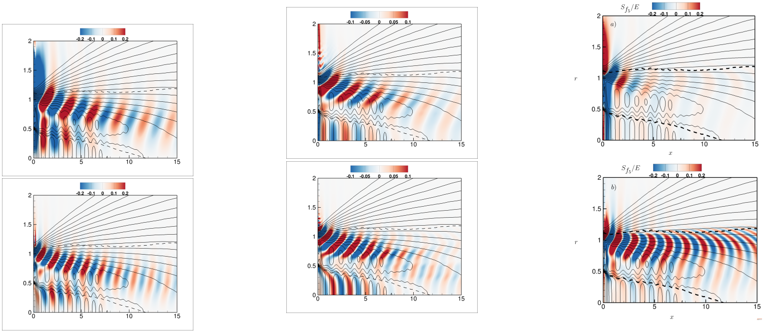
- solid lines : iso $\bar{u}_x$, dashed lines : lines of inflection points of $\bar{u}_x$
- Frequency affects the sensitivity similarly to the instability
- sensitivity distribution is higher along the second shear layer
- The spatial periodicity (wave length) and the frequency of the instability imposed the streamwise distribution of sensitivity
- The sensitivities isolines follows the mean profile variations(shocks) and the pressure wave (KH_1 for $x < 8$ and KH_2 for $x > 8$)

Sensitivity

f_2 : ρu_r | f_4 : ρu_x | f_5 : p

$S_t = 0.6$

$S_t = 1.0$



- clearly, increasing frequency wave increase the number of high sensitivity spots
- for f_5 : spots of sensitivity distrubed along the secondary inflectional line in the far downstream contrarily to the other forcing types
- Influence of the primary inflectional line with intense shocks.

Summary and perspectives

- ## Some concluding remarks
  1. Sensitivity of flow perturbations to any forcing are strongly related to the flow instability patterns, their growth rates and their wave length
  2. the most unstable KH mode governs the sensitivity
  3. inflectionnal point lines bound the sensitivity zone
  4. but sensitivity spots strongly depend on the forcing type
  5. instability at the nozzle exit enhances the sensitivities $\Longrightarrow$ active control should be here !
- ## Current works
  1. far-field noise investigation with FW-H analogy
  2. Analysis of the sound emission and directivities with mean flow/perturbation/sensitivities
- ## Some improvements and perspectives
  1. to design a sensitivity model of the far-field noise emission
  2. Test some simple actuations close to the nozzle exit (wave control)

Acknowledgements

- European Marie Curie Programme : AeroTraNet
- Calmip center (computer ressources in Midi-Pyrénées)

thank you for your attention !

Additionnal slides : far-field pressure field ...

Advertising ...

Validation of the code

- Validation on single stream jet :
  - Brazier and Léon's work (ONERA)
  - incompressible (Yen and Messerchmit-1998) , $\rightarrow$ Ansaldi et al, AIAA 2015-2215
  - supersonic (Tam and Burton - 1984, YM99) , $\rightarrow$ Ansaldi et al, AIAA 2016-3052
- Analysis of the single subsonic stream jet from LES (Cerfacs)

Acoustics

1. Advanced Ffowcs Williams and Hawkings (Antares, Cerfacs)
2. Validation : AIAA-2016-3059 (Di Stefano et al)
3. Pressure : inclinaison of 6 deg

Acoustics: far-field

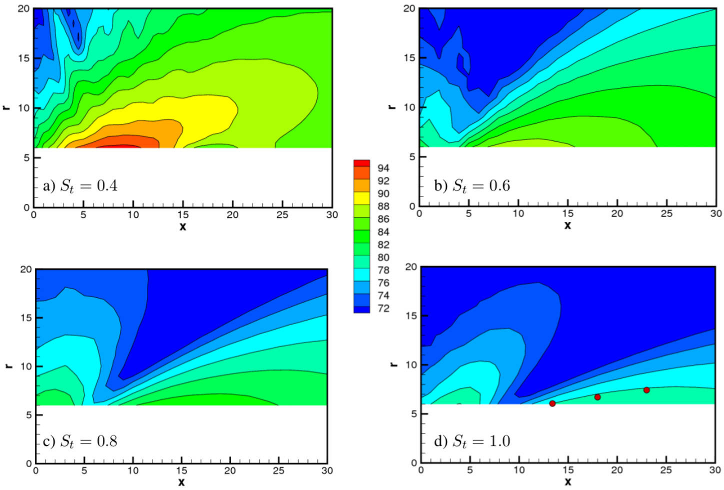
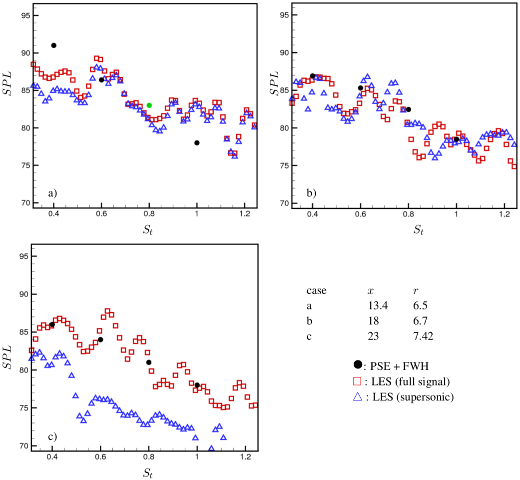


Figure 1.6 - *SPL in dB in the far-field for 4 Strouhal number. The filled points of figure d) indicate the location of the probes*

Acoustics : SPL along a line



case	x	r
a	13.4	6.5
b	18	6.7
c	23	7.42

●: PSE + FWH
□ : LES (full signal)
△ : LES (supersonic)

Figure 1.7 - *SPL in dB in the far-field for 3 locations along a line inclined at* 6°. *The green filled points of figure a) indicate the location of reference for the perturbation amplitude with the PSE*